

Technical Note

Intracoronary MR Imaging Using a 0.014-Inch MR Imaging-Guidewire: Toward MRI-Guided Coronary Interventions

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Purpose: To validate the feasibility of using a newly designed MR imaging-guidewire (MRIG) to guide angioplasty balloon placement in coronary arteries.

Materials and Methods: A custom gold/silver/Nitinol/MP35N-based, 0.014-inch MRIG was manufactured. To test its mechanical performance we used the new MRIG to catheterize the left coronary arteries of three dogs under x-ray fluoroscopy. To further validate the feasibility of using the MRIG to generate intracoronary MR imaging, we positioned the MRIG, along with a dilation-perfusion balloon catheter, into the left coronary arteries of an additional three dogs. Longitudinal and four-chamber views of cine cardiac MR images were obtained using a fast gradient recalled echo (FGRE) sequence (TR/TE/FA = 5.2 msec/1.6 msec/20°, field of view [FOV] = 32 × 32 cm, thickness = 5 mm, space = 2 mm, matrix = 256 × 160, number of excites [NEX] = 0.5, and bandwidth [BW] = 32 kHz). Then three-dimensional (3D) MR coronary angiography of the left coronary arteries was obtained using a fast imaging employing steady-state acquisition (FIESTA) sequence. We subsequently used the MRIG, at a receive-only mode, to generate intracoronary MR images using FGRE (TR/TE/FA = 7.2 msec/3.5 msec/20°, FOV = 18 × 18 cm, thickness = 3 mm, space = 0.5 mm, matrix = 256 × 256, NEX = 0.5, and BW = 32 kHz).

Results: In all six animals the left main coronary arteries were successfully catheterized. 3D MR imaging displayed left coronary artery branches. Intracoronary MR imaging demonstrated the inflated balloons as a “train track” or a bright, thick ring at different views.

Conclusion: This study demonstrates the potential of using this newly designed gold/silver/Nitinol/MP35N-based, 0.014-inch MRIG to catheterize coronary arteries and, thus, generate intracoronary MR imaging with balloon inflation.

Key Words: MRI; coronary intervention; MR imaging guidewire; percutaneous transluminal coronary angioplasty (PTCA)

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X-RAY ANGIOGRAPHY has dominated percutaneous transluminal coronary angioplasty (PTCA) and other intracoronary interventions for decades. However, the limitation with this technique is that the x-ray contrast agent can outline only the vessel lumen. Magnetic resonance imaging (MRI), which provides not only anatomical images of the heart but also functional as well as metabolic information, may become a “one-stop-shop” imaging modality for cardiovascular interventions, such as MRI-guided percutaneous transluminal coronary angioplasty (PTCA), stent placement, and gene therapy (1–3).

To develop new techniques of endovascular interventions under MRI guidance, previous efforts from different groups have focused on the development of active and passive MR trackable interventional devices (4,5) and real-time MR imaging techniques (6). One of the advances in this research field was the development of an intravascular MR imaging guidewire (MRIG) (7), which provided two basic functions of 1) an intravascular MR receiver to generate high-resolution MR imaging of vessel wall/plaques; and 2) a conventional guidewire to guide endovascular interventions, such as balloon angioplasty and stent placement (8). Subsequently, the function of the MRIG has been extended to produce intravascular local radiofrequency (RF) heating for thermal enhancement of vascular gene therapy (9–12).

Currently, the MRIG is made of Nitinol, 0.032-inch in diameter (Surgi-Vision, Columbia, MD), which has been approved by the FDA. This size of MRIG can be primarily used in the middle- and large-sized peripheral arteries, but is not suitable for intracoronary artery imaging and interventions. To solve this problem, a

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novel, clinical-sized, 0.014-inch MRIG was built by cladding and plating highly electrically conductive materials, such as gold and silver, onto superelastic, MRI-compatible materials, such as Nitinol and MP35N (13). Similar to a 0.032-inch MRIG, this new generation of MRIG is expected to maintain 1) the suitable flexibility and maneuverability for guiding endovascular interventions; and 2) the excellent electrical conductivity for generating intravascular high signal-to-noise ratio (SNR) MR imaging (13).

The aim of the present study was to apply this new 0.014-inch MRIG in coronary artery interventions. We attempted to validate the feasibility of using this new 0.014-inch MRIG to catheterize the coronary arteries, guide the placement of balloon catheters into the coronary arteries, and generate intracoronary artery MR imaging to visualize the balloon inflations.

MATERIALS AND METHODS

Animals

In vivo experiments were performed on six healthy dogs. Animals were treated according to the guidelines for laboratory animal care of the National Society for Medical Research, and the *Guide for the Care and Use of Laboratory Animals* (NIH publication 80-23, revised 1985). The animal protocol was approved by the Animal Care and Use Committee of our institution.

Gold/Silver/Nitinol-Based, 0.014-inch MRIG

The details for manufacturing the custom 0.014-inch MRIG have been described elsewhere (13). Briefly, the 0.014-inch MRIG was built by plating/cladding highly electrically conductive materials, silver or gold, over the inside and outside of coaxial conductors, which were made of superelastic and nonmagnetic materials, Nitinol, and MP35N. Then we assembled the silver/gold plated conductors with a polymer-insulated tube to construct a coaxial cable, 0.014-inch in diameter. This design of the MRIG can reduce the MR signal attenuation to achieve a high SNR ratio, while maintaining the mechanical properties of the MRIG for performing intravascular interventions. To enable the efficient catheterization of the coronary artery, the tip of the MRIG, a 6.5-cm extension of the inner conductor, was mounted with a hydrophobic spring coil similar to the tip of a conventional guidewire. The other end of the MRIG was connected to an MRI scanner through a tuning/matching/decoupling circuit (13).

In Vivo Experiments

Each dog was first anesthetized with intramuscular administration of a mixture of ketamine (35 mg/kg) and acepromazine (0.75 mg/kg), as well as atropine (0.5 mg/kg). Then pentobarbital (25 mg/kg) was administered intravenously, via a leg vein, to induce general anesthesia for surgery. Anesthesia was maintained with inhalation of isoflurane (1%–2%). Through a carotid artery cutdown, a 7F introducer sheath (Meditech/Boston Scientific, Boston, MA) was placed into the artery, and then heparin (100 IU/kg) was adminis-

tered. To test the mechanical property of the new 0.014-inch MRIG, we used it to catheterize the left coronary arteries of three dogs under x-ray fluoroscopy. Through the introducer sheath, an MR-compatible 5-6F guiding catheter (AngioDynamic, Queensbury, NY), along with the 0.014-inch gold/silver/Nitinol/MP35N-MRIG, was inserted to catheterize one of the left coronary artery branches, the left anterior descending (LAD) branch or circumflex branch, of each animal.

We used an additional three dogs to further validate the feasibility of using the MRIG to generate intracoronary MR imaging for monitoring of intracoronary interventions. The MRIG was first placed within a 2.5-mm dilation-perfusion balloon catheter (Remedy, Boston Scientific, Watertown, MA), with the MRIG flexible tip beyond the balloon tip. Then both the MRIG and the balloon catheter were advanced into the coronary arteries, with the flexible tip of the MRIG functioning as a conventional guidewire. The accurate location of the MRIG within the coronary artery was confirmed under x-ray by adjusting the inner-outer conductor junction of the MRIG at the center of the intended coronary artery segment. Once the MRIG and the balloon catheter were placed the animal was transported to an MR scanner for intracoronary MR imaging.

MR Imaging

The animal was placed on the table of a GE 1.5 T CV/i MR scanner (maximum gradient amplitude at 40 mT/m, and maximum slew rate at 150 T/m/s) in the supine position with feet first. The left chest of each animal was shaved, cleaned, and then 4–6 electrodes were attached to achieve optimal ECG signal. With a cardiac ECG monitor system (Magnitude, Invivo, Latham, NY), the cardiac trigger signal was acquired, monitored, and sent to the interface of the MRI physiological acquisition controller. Two five-inch surface coils were placed on the anterior chest bilaterally and connected to the MR scanner via a dual adaptor or a phased-array adaptor. Through a tuning/matching/decoupling box the MRIG was then connected to a receiver channel of the scanner.

The sagittal and axial scout images were acquired using a fast gradient-echo (FGRE) pulse sequence (TR/TE/FA = 6.7 msec/3.2 msec/20°, field of view [FOV] = 32 × 32 cm, thickness = 5 mm, space = 0.5 mm, matrix = 256 × 160, number of excitations [NEX] = 0.5, and bandwidth [BW] = 32 kHz), with cardiac trigger and breath-holding by temporarily turning off the operation of the anesthesia machine. Based on the axial image, three slices of long axial cine images were obtained using FGRE (TR/TE/FA = 5.2 msec/1.6 msec/20°, FOV = 32 × 32 cm, thickness = 5 mm, space = 2 mm, matrix = 256 × 160, and NEX = 0.5). Then cine MR images at four-chamber view were obtained with the same pulse sequence and imaging parameters. On the cine image the proximal left and the right coronary arteries could be visualized as two bright dots. Three-dimensional (3D) coronary MR angiography was then acquired along the line between the two bright dots, using a 3D fast imaging employing steady-state acquisition (FIESTA) sequence (TR/TE/FA = 4.5 msec/2.1

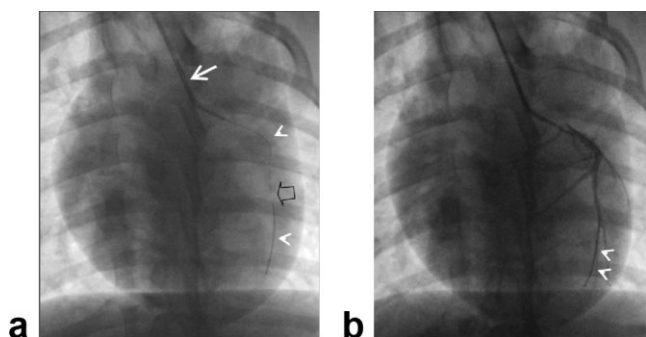


Figure 1. X-ray fluoroscopic imaging of the heart of a dog. **a:** Via the guiding catheter (arrow), the 0.014-inch MRIG (arrowheads) is positioned in the left anterior descending (LAD) of the coronary artery. The open arrow indicates the inner-outer junction of the MRIG. **b:** Coronary angiography confirms the location of the MRIG (arrowhead) in the LAD.

msec/60°, matrix = 512×512 , thickness = 2.6, SP = 1.3 mm, BW = 125 kHz, FOV = 28×28 cm, NEX = 0.75, and fat saturation). The optimal time delay for FIESTA was determined by analyzing the cine images with minimal coronary artery movement. Then 3D coronary MR angiography using the same FIESTA sequence at 1-mm thickness with no gap was performed to achieve the coronary angiographies of either LAD or circumflex branch.

Based on MR coronary angiography, we subsequently inflated the balloon with a net 6% concentration of Magnevist (469 mg/mL, Berlex Laboratories, Wayne, NJ). We then operated the 0.014-inch MRIG, at a receive-only mode, to generate longitudinal and axial intracoronary MR images using FGRE (TR/TE/FA = 7.2 msec/3.5 msec/20°, FOV = 18×18 cm, thickness = 3 mm, space = 0.5 mm, matrix = 256×256 , NEX = 0.5, and BW = 32 kHz).

RESULTS

In all six animals the left main coronary arteries were successfully catheterized and the MRIG was accurately positioned into the left coronary artery branches, either the LAD or the circumflex artery (Fig. 1). 3D FIESTA MR imaging showed clearly the courses of the LAD or circumflex arteries (Fig. 2). Intracoronary MR imaging demonstrated the inflated balloon as a “train track” on the longitudinal view and as a bright, thick ring on the axial view (Fig. 3).

DISCUSSION

MRI-guided coronary intervention is a challenging task for several reasons. First, the coronary arteries are small in diameter and tortuous, with complex trajectories, which make the catheterization procedure more difficult than those performed in the peripheral arteries. Second, the heart is beating and moving with respiration, which creates stronger motion artifacts than other organs and systems. To deal with the first problem we built a small-sized MRIG, 0.014-inch in diameter, which is a standard size of a conventional guidewire

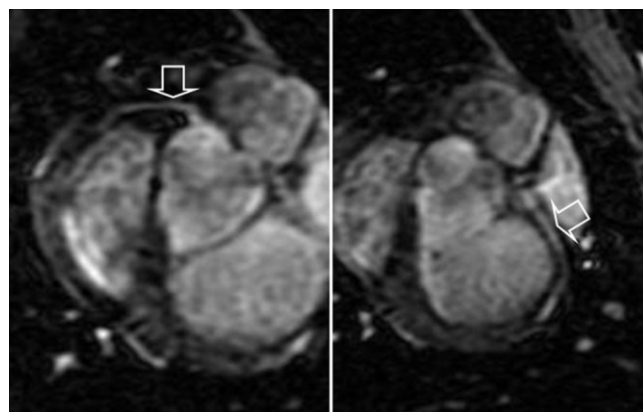


Figure 2. MR coronary angiography (MRCA), demonstrating the courses of the right coronary artery (arrow in **a**) and the left anterior descending (LAD) artery (arrow in **b**). MR parameters: FIESTA, 4.5 msec/2.1 msec/20°, TR/TE/FA, 512×512 matrix, 2.6 mm slice thickness, 2.8×2.8 cm FOV, and fat saturation.

used for guiding interventions in the coronary arteries of humans. In the current study we initially validated the feasibility of using such thin MRIG to perform coronary catheterizations and generate intracoronary imaging of the balloon inflation. We were expecting that the 0.014-inch MRIG should enable us to perform intracoronary interventions, such as balloon angioplasty and stent placement, as well as gene delivery/therapy, in the MRI environment in the near future.

In this study we used the new MRIG to catheterize the coronary arteries and guide the placement of balloon catheters under x-ray fluoroscopy. Ideally, catheterization of the coronary arteries should be performed under MR fluoroscopy. The reasons we used x-ray fluoroscopy for catheterization included 1) with current technology, MR fluoroscopy has not achieved “real-time” imaging, as yet, as x-ray fluoroscopy does; and 2) intracoronary MR tracking of MRIGs has been extensively investigated in previous studies (1,2). In addition, since the specific guiding catheters were not available for the catheterization of dog coronary arteries, we had to use the com-

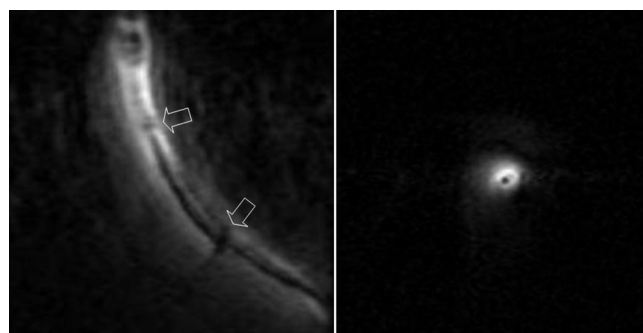


Figure 3. Intracoronary MR imaging of left anterior descending (LAD) artery using the 0.014-inch MRIG. **a:** The longitudinal view image, showing the inflated balloon as a “train-track,” with two balloon metal marks (arrows). **b:** The axial view image, showing the inflated balloon as a bright, thick ring and the MRIG as a dark spot within the balloon.

mercially available guiding catheters used for humans. The tip configurations of these guiding catheters might not be suitable for catheterization of dog coronary arteries. As a result, it might require more time to catheterize the coronary arteries under MRI than under x-ray fluoroscopy. Because of these factors we first positioned the MRIG under x-ray fluoroscopy guidance and then generated intracoronary MR imaging by transporting the animals to a clinical MRI scanner. This inconvenient procedure may be eliminated using a hybrid interventional x-ray/MR system that combines the angiography lab with an MR scanner, ie, either Philips X-MRI or Siemens Angio-MRI (14).

In the current study we did not attempt to use a black-blood pulse sequence for MR imaging of the coronary artery walls with the MRIG. One reason is that the inflated balloon may block the blood flow in the coronary artery. The second reason is that the black-blood pulse sequence is relatively slow, which may not help us to overcome the motion artifacts created by irregular cardiac beating due to the intracoronary placement of MRIGs and balloon catheters. Rather than a fast spin echo (FSE) pulse sequence, we achieved intracoronary MR imaging by using a fast gradient-recall echo sequence (FGRE), which generated sufficient imaging quality to visualize the intracoronary balloon inflation. Since this study primarily focused on the pre-clinical application of the new 0.014-inch MRIG in coronary arteries, we did not attempt to evaluate the potential heating that could be generated by the interaction between the MRIG's conductors and the B1 fields. A previous study had reported no significant thermal effect and damages with a 0.032-inch MRIG (15).

Since the 0.014-MRIG was assembled manually, it was difficult to control its mechanical uniformity and the electrical properties during manufacturing. However, the MRIG does, indeed, receive MR signals from the inflated balloon, which thus may permit the monitoring of intracoronary interventional procedures, such as MR-guided PTCA and stent placement, as well as gene delivery/therapy, in the future. It is known that cardiac MRI provides more comprehensive information about morphological and pathohistological changes in the diseased myocardium. Cardiac MR perfusion imaging, pre- and postinterventions, may help physicians to evaluate the therapeutic effectiveness of MRI-guided intracoronary interventions. In combination with these advanced cardiovascular MRI techniques, development of intracoronary MRI imaging may open a new avenue to the efficient management of atherosclerotic cardiovascular disease.

In conclusion, this study demonstrates the potential of using the gold/silver/Nitinol/MP35N-based, 0.014-inch MRIG to catheterize the coronary arteries, to guide the positioning of the balloon catheter into the coronary arteries, and thereafter to generate intracoronary MR imaging of the inflated balloons. With continuous refinement, the 0.014-inch MRIG-based imaging technique may facilitate MRI-guided interventions, such as MR-guided PTCA and stent placement, as well as gene/drug delivery and therapy of atherosclerotic coronary diseases in an MRI environment.

REFERENCES

1. Serfaty JM, Yang X, Aksit P, Quick HH, Solaiyappan M, Atalar E. Toward MRI-guided coronary catheterization: visualization of guiding catheters, guidewires, and anatomy in real time. *J Magn Reson Imaging* 2000;12:590-594.
2. Serfaty JM, Yang X, Foo TK, Kumar A, Derbyshire A, Atalar E. MRI-guided coronary catheterization and PTCA: a feasibility study on a dog model. *Magn Reson Med* 2003;49:258-263.
3. Yang X. Imaging of vascular gene therapy. *Radiology* 2003;228:36-49.
4. Duerk JL, Wong EY, Lewin JS. A brief review of hardware for catheter tracking in magnetic resonance imaging. *Magma* 2002;13:199-208.
5. Zhang S, Rafie S, Chen Y, et al. In vivo cardiovascular catheterization under real-time MRI guidance. *J Magn Reson Imaging* 2006;24:914-917.
6. Aksit P, Derbyshire JA, Serfaty JM, Atalar E. Multiple field of view MR fluoroscopy. *Magn Reson Med* 2002;47:53-60.
7. Ocali O, Atalar E. Intravascular magnetic resonance imaging using a loopless catheter antenna. *Magn Reson Med* 1997;37:112-118.
8. Yang X, Atalar E. Intravascular MR imaging-guided balloon angioplasty with an MR imaging guide wire: feasibility study in rabbits. *Radiology* 2000;217:501-506.
9. Qiu B, El-Sharkawy AM, Paliwal V, et al. Simultaneous radiofrequency (RF) heating and magnetic resonance (MR) thermal mapping using an intravascular MR imaging/RF heating system. *Magn Reson Med* 2005;54:226-230.
10. Qiu B, Yeung CJ, Du X, Atalar E, Yang X. Development of an intravascular heating source using an MR imaging guidewire. *J Magn Reson Imaging* 2002;16:716-720.
11. Du X, Qiu B, Zhan X, et al. Radiofrequency-enhanced vascular gene transduction and expression for intravascular MR imaging-guided therapy: feasibility study in pigs. *Radiology* 2005;236:939-944.
12. Gao F, Qiu B, Kar S, Zhan X, Hofmann L, Yang X. Intravascular magnetic resonance/radiofrequency may enhance gene therapy for prevention of in-stent neointimal hyperplasia. *Acad Radiol* 2006;13:526-530.
13. Qiu B, Karmarkar P, Brushett C, et al. Development of a 0.014-inch magnetic resonance imaging guidewire. *Magn Reson Med* 2005;53:986-990.
14. Merkle EM, Lewin JS, Liebenthal R, Lorenz CH. The interventional MR imaging suite: magnet designs and equipment requirements. *Magn Reson Imaging Clin N Am* 2005;13:401-413.
15. Yang X, Yeung C, Ji H, Serfaty J, Atalar E. Thermal effect of intravascular MR imaging using an MR imaging-guidewire: an in vivo laboratory and histopathological evaluation. *Med Sci Monit* 2002;8:MT113-117.